

Orbital Debris,
the problem and the mitigation

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Introduction

This book covers the topic of Orbital debris, what it is, where it comes from, what problems it introduces, and how to deal with it. . Putting a communications satellite in synchronous orbit will set you back 100's of millions of dollars. Once on orbit, you hope it survived the launch environment, and operates correctly. You further hope it works at least for its design lifetime, and as long as possible. This approach, based on good engineering design practices, lessons learned, and hope, it the equivalent of buying a new Tesla with non-rechargeable batteries, and driving it until it stops. Then buying a new one. Regardless of what you were told, there is no satellite fairy with a magic wand. There will be some serious trash-talk here. This third edition has some breaking news that happened as the second edition was published.

The Author

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briefly on the Hubble Space Telescope repair missions.

A note on Units

I am fairly conversant in both English and Metric units (what is the metric equivalent of furlongs per fortnight?). Metric (SI) is mandated for NASA usage now, for interchangeability with our partner space faring nations. When a lot of the legacy flights discussed here were flown, English units were the norm. I have tried to keep the units comparable to the mission at the time. Conversions are easy enough, but units conversion is a source of error. It's not what you know about units and measurement, its how you think. And, I still think English units (even the English use Metric now), and convert in my head or on my phone.

For scientific/engineering work, the Metric system is well thought out. For artisans, the English system served well, as most units were divided by 2. Which is easy. Fold the cloth. Hopefully, when we are all taught Metric first, some one will still remember the back conversions. You just need a good slide rule....

The debris problem

Orbital debris can come from many sources. It can be naturally occurring rocks and captured meteoroids. It can come from satellites collisions and explosions. Liquid fuel, from a dead satellite or leakage, freezes in space and provides yet more debris problems. There have been 5 known collisions of satellites in orbit so far.

All of the junk, down to the size of bolts, is tracked by the U.S. Air Force. They know of 18,000 objects in orbit, of which 1,400 are operational satellites. A good job for a robotic servicer in LEO would be to collect the trash, put it in a canister, and kick it off to re-enter and burn in the atmosphere. There are estimated to be 170 million chunks, smaller than a centimeter, any of which can ruin your mission.

Known space debris includes Astronaut Ed White's outer glove, lost on his space walk; Michael Collins's camera from Gemini-10; a wrench, pair of pliers, and a tooth brush; and a complete tool bag from an STS-26 EVA.

In addition to our own junk, space itself provides dust particles, up to and including asteroids capable of ending all life on Earth with a collision.

For mitigation, the ISS uses Whipple shielding, named for its inventor. This uses a thin outer bumper, spaced away from the hull. The idea is, the bumper breaks up the debris so that penetration doesn't happen. It works most of the time. Think of it as the ISS's bullet proof vest. It works best with a foam material behind it.

There have been on-orbit tests of anti-satellite weapons, by the U.S., Russia, and China which resulted in a large amount of debris. In addition, failed on-orbit rendezvous usually involved a low speed collision, and more debris creation. There was the 1996 collision between the French Cerise military reconnaissance satellite and debris from the Ariane rocket. In addition, a 2009 collision between the Iridium 33 communications satellite and the derelict Russian Kosmos 2251 resulted in the destruction of both satellites, and a big mess. There was the 2013 collision between debris from the Chinese Fengyun FY-1C satellite and the Russian BLITS nano-satellite. We should also mention the 2013 collision between two CubeSats, Ecuador's NEE-01 Pegaso and Argentina's CubeBug-1, and the particles of a debris cloud around a Russian Tsyklon-3 upper stage from the launch of Kosmos 1666. A 1985 U.S. Anti-satellite test created thousands pieces of debris greater than 1 cm. Most of this reentered the atmosphere within 10 years.

In 2009, a U.S. Iridium satellite collided with a defunct Russian Cosmos satellite, producing some 2,100 pieces of debris. There is a catastrophic collision every 5-9 years.

China is responsible for the largest single space debris incident

resulting from a 2007 test of anti-satellite weapons. It transformed one satellite into nearly 2,500 pieces, golf-ball size or larger. The test was conducted in an orbital zone where most near-Earth missions are located. Some satellites have had to maneuver to avoid collisions.

NASA says that at least one piece of space debris falls to Earth daily, and has for the past 50 years. There have been injuries, such as the Japanese fishermen hit in 1969. A lady in Oklahoma was hit by a piece of debris in 1997 but was not injured. This turned out to be a piece of a Delta-II rocket propellant tank.

Zombie Sats

Zombie sats are non-functioning satellites in orbit. They may have experienced a failure, and are no longer functional. They remain in the same slowly-decaying orbit, however. The Intelsat Galaxy-15 is an example. It was in geostationary orbit when the ground lost control, and it began to drift. There was a potential of collision with other, operating satellites. Later, control was recovered, and it was directed back to its correct orbital position.

The first U. S. satellite, Vanguard-1, and its upper stage are still in-orbit. It was launched in 1958. The Soviet-era RORSAT, with its BES-5 nuclear reactor, is still in orbit. In 2015, the USAF Defense Meteorological Satellite (Military equivalent of the GOES weather satellite) exploded in orbit, creating some 150 chunks of satellite in orbit.

Of the 7,000 or so satellites placed into Earth orbit so far, 1,500 are still functioning. The rest are zombie-Sats.

Satellite on-orbit collision

There was a collision between two satellites occurred in February of 2009. One was a Russian Strela-class military satellite, massing 950 kilograms. The other was the commercial Iridium-33 communications satellite. What was the cause? They were in the

same place at the same time. The Russian spacecraft had been deactivated, and was classified as space debris. The Iridium was operational, and was destroyed.

And, the bad news is, the collision created a thousand pieces of space debris larger than 4 inches, and many more smaller ones. In March 2012, a piece of the KOSMOS 2251 passed by the International Space Station, prompting the crew to take refuge in the attached Soyuz return craft as a precaution. The ISS frequently does obstacle avoidance maneuvers.

The SNAP-10 spacecraft was launched in 1965. It included a nuclear fission device for electrical power. It operated for 45 days before an electrical failure. It was placed in a 1,300 km orbit, where it is expected to remain for around 4,000 years. It was noticed that in 1979, the spacecraft was shedding traceable debris. It is not known if radioactive material is included.

Booster debris

After the first stage of the launcher has done its job, it usually crashes into a remote part of the ocean. The next stage may also. The final stage usually accompanies the payload into orbit. The Shuttles' boosters were dropped in the Atlantic, recovered, refurbished, and reused. The large liquid fuel tank was crashed into a remote part of the ocean. These are a particular problem, because they always have residual fuel, which decomposes.

A Chinese Long March-4 upper stage exploded in orbit in 2000, creating a vast debris cloud. A Russian booster exploded in 2007, captured in images. The debris cloud was tracked on radar. More than 1,000 fragments were identified.

In 2001, part of a U. S. upper stage of the NavStar-32 satellite crashed into the Saudi Arabian desert.

The graveyard orbit.

A graveyard orbit is a disposal area for non-operational spacecraft.

This is particularly important for the geosynchronous missions, which tend to be commercial. The geo-sync graveyard orbit is a few hundred kilometers higher than the operational orbit. It is much less costly in propellant to place that defunct spacecraft in the slightly higher orbit, than to re-enter it. This doesn't solve the problem completely, but postpones it until servicing options become available.

As part of the licensing process for satellites providing communication services from geo-sync, a requirement is imposed to move the spacecraft to a graveyard orbit at the end of its operational life.

Where do old, non-operational spacecraft wind up? Mostly in the ocean. The Chinese Tiangong-1 space station will reenter to atmosphere sometime around when this book gets wrapped up. Ground controllers have lost control, so they don't know where it will come down, until shortly before it does.

The point in the Oceans farthest from land is called the pole of inaccessibility. This is the best point to aim for, if you're de-orbiting something large. It happens to be located in the South Pacific, some 1,600 miles south of the Pitcairn Islands. There are some 260 satellites on the ocean floor at that point. This will be an interesting place for future archaeologists. Among other things, the 120-ton MIR space station is there. It's entry into the water was observed by fishermen. This is also where supply modules from the ISS, loaded with trash, are sent. Sometimes, things don't quite work out. 36 tons of Salyut Space Station came down in South America.

What did we do with the Apollo hardware?

The Apollo missions to the moon consisted of the crewed Apollo capsule, the Lunar Excursion Module, and the Service Module. Only the crewed capsule and the service module returned from the moon. Only the crewed capsule re-entered the atmosphere. What happened to all the other stuff?

The Apollo payload consisted of the Launch Escape System, the

Apollo capsule, the service module, and the lunar lander. The launch escape system (LES) was located above the Apollo capsule and was jettisoned early in flight. The Lunar Excursion Module (LEM) was stored behind the service module. Once in Earth orbit, the capsule and Service Module were separated, the capsule rotated 180 degrees, and docked to the Lunar module. The lunar package was then separated from the third stage. The capsule, lander, and service module left Earth orbit heading for the moon, while the third stage was commanded into a solar orbit, to get it out of the way.

The Saturn-V was a three-stage, human-rated launch vehicle. Thirteen of the vehicles were launched. All three stages used the same fuel and oxidizer, liquid hydrogen and liquid oxygen (LOX). The first stage, S1C, had a dry weight of around 130 tons. It fell into the Atlantic Ocean when it had done its job. The second stage, about 40 tons dry, continued into Earth orbit with the crewed capsule. The third stage, S-IVB, was sent into a solar orbit. During the Apollo 13, 14, 15, 16, and 17, the S-IVB stages were deliberately crashed into the Moon to perform seismic measurements used for characterizing the lunar interior.

The Apollo command module with the Astronauts re-entered the atmosphere, and landed in the Ocean. Most of these are now in Museums. The Service Modules, returning from the moon, were jettisoned before reentry and burned in the atmosphere.

The Lunar Excursion Modules got two Astronauts to the lunar surface, and later returned them to the orbiting Command Module. The LEM was made in two parts, and the lander, or lower, section remained on the Moon.

Most of the crewed portion of the LEM's were deliberately crashed into the lunar surface, to provide data for the seismic instruments left on the surface. This includes the lunar modules, *Eagle* and *Intrepid*. The Lunar Module *Aquarius*, from Apollo-13, burned up in Earth's atmosphere in April, 1970. It had been the lifeboat for the astronauts, after the Service Module exploded on the way to the Moon. It was jettisoned before the manned capsule reentered the

atmosphere. The Lunar Modules *Antares*, *Falcon*, and *Challenger* impacted the lunar surface.

SMM

The Solar Maximum Mission satellite, a GSFC mission, was designed to investigate Solar phenomena, particularly solar flares. It was launched on February 14, 1980.

In January 1981, three fuses in the SMM's attitude control system failed, causing it to rely on its magnetic torquers to maintain attitude. In this mode, only three of the seven instruments were usable, as the others required the satellite to be accurately pointed at the Sun. The use of the satellite's magnetic torquers prevented the satellite from being used in a stable position and caused it to "wobble" in its orbit.

Although not unique in this endeavor, the SMM was notable in that its useful lifetime was significantly increased by the direct intervention of a manned space repair mission. During STS-41-C in 1984, the Space Shuttle *Challenger* intercepted the SMM, maneuvering it into the shuttle's payload bay for maintenance and repairs. SMM had been fitted with a shuttle "grapple fixture" so that the shuttle's robot arm could grab it. During the mission, the SMM's entire attitude control system module and the electronics module for the an instrument were replaced, and a gas cover was placed over another instrument. SMM was the first on-orbit servicing mission in history.

The success of the SMM repair demonstrated beyond a doubt the feasibility of servicing a spacecraft in orbit, but at a high level of complexity, involving a Shuttle mission, and trained astronauts. These repairs were successfully completed, adding five years to the satellites working life. The spacecraft reentered the atmosphere and burned in December of 1989, taking some of the author's best flight software with it.

What is most interesting was an analysis of the modules brought

back, after a 4-year period in orbit. Much was learned about the debris flux, and composition. This was from surfaces not specifically designed for particle collection, specifically, the thermal blankets. Analysis of these revealed valuable information on penetration depth, impact velocity, and particle size.

In addition, the returned hardware from the Hubble Space Telescope Servicing Missions provided new insight on space debris strikes. These included the large solar arrays. This evidence was used to validate debris models.

Space Station Mir

Quite a lot of lessons were learned from the impact of small debris on the Soviet Space Station Mir. The Environmental Effects payload was returned and studied, adding to knowledge applied to the ISS. It was in orbit for 3,644 days before reentering the atmosphere. In an amusing incident, a Kvant re-supply module was having trouble docking with the station. An EVA revealed a trash bag in the way. Seems you can't just leave the trash outside the door, in orbit, and have it picked up.

MIR was in a near-circular orbit of 354-375 kilometers. Atmospheric drag continually lowered the orbit, and it was re-boosted by the resupply vehicles. The station reentered and burned, landing in the South Pacific in March of 2001. The facility had been designed with a 5-year lifetime goal, but lasted 15.

Shuttle

Since the Shuttle orbiter returned to the ground and landed on a runway after its missions, it was carefully studied for the effects of collisions with orbital debris. This generally included chipping of the windows, and minor damage to the thermal tiles, which tended to contain the debris. In addition, the Shuttle's orbit during a mission was carefully inspected for detectable debris, and it could maneuver to prevent collisions. STS mission 48 in 1991 had the first avoidance maneuver, to miss Kosmos 955. Several other missions

had avoidance maneuvers. On missions to the Space Station, the facility was approached so the Shuttle remained in the Stations debris shadow.

In 2006, a chunk of circuit board in orbit damaged one of Shuttle Atlantis' radiator panels. Later, a similar thing happened to Shuttle Endeavor.

In the 2003 Shuttle Columbia disaster, a large amount of debris hit the ground in a long path, as the Shuttle disintegrated during re-entry. Debris was strewn across hundreds of miles of Texas and Louisiana. The accident investigation board found that a hole had been punched in the leading edge of a wing, by a piece of insulating foam broken off the external fuel tank early in the ascent. There were 84,000 pieces of debris collected. This is stored at the Kennedy Space Center.

ISS

In normal operations, the Earth's magnetic field deflects charged particles from the station. Energetic space particles may pass through the station with negligible effect. Space debris is a problem, from discarded bolts to Zombie-Sats. These are all tracked, and on rare occasion, the station needs to do a damage avoidance maneuver to avoid a collision. To date, no evacuation of the Station has been necessary. It does a debris avoidance maneuver if there is a greater than 1 in 10,000 chance of a strike. This tends to happen about once per year.

If the warning comes too late for maneuvers (usually a few days), the crew shelters in the attached return capsule.

Trash comes down, with the simple yet costly expedient of having a logistics carrier burn up in the atmosphere on reentry.

The current ISS will reach end-of-life in the 2020's, and is too big to be allowed to re-enter in one piece. One or more follow-on stations will be built in orbit, re-using some modules from the ISS, and new modules launched from the ground. This is possible due to the modular nature of the ISS, and the lessons-learned during its on-

orbit construction and use.

Russia currently has plans to remove some of its modules, and re-purpose them into a new facility, the Orbital Piloted Assembly and Experiment Complex (OPSEK). This is based on an estimated life on-orbit of 30 years, from the MIR experience.

The various nations that own parts of the station are responsible for their disposal. If the parts can not be re-purposed, they will be re-entered into the atmosphere in a controlled manner.

The LDEF Mission

The Long Duration Exposure Mission was placed in a 275 mile orbit by Space Shuttle Challenger in 1984. It spent 69 months in space, collecting information on long term exposure of materials to the space environment, and the meteoroid environment. It was to be periodically returned to Earth, refurbished, and re-orbited, but instead, the original mission was extended. It was recovered and returned to Earth by Shuttle Columbia. Although it was expected that meteoroid impacts would be the major phenomena, over 30% of the observed impacts were from debris. This led to the realization that the debris environment was larger than suspected. In some cases, the impacting body was still embedded in LDEF's structure. There was penetration of up to 40 mils of aluminum observed. In total, 34,000 impacts were cataloged, the largest being 0.57 cm.

Characterizing the “space dust” environment, it is estimated that over 14 million tons fall to the Earth's surface each year. The number of meteors entering the atmosphere is estimated to be between 10 and 20,000 tons. Most of these burn in the atmosphere, but when they do hit, they can be catastrophic. Generally, if the chunk is big enough to do damage, it can be tracked. Sometimes you miss them. Like in the Urals in Russia in February, 2013. This injured hundreds, but did not hit anything in the town. There could have been hundreds of deaths.

Saturn-Pegasus

The Pegasus payload was intended to supply much-needed information on the near-space meteoroid environment, that would influence the design of manned spacecraft. The main reason this information was vital was that space missions were lasting longer, and getting bigger. They were puncture targets for small chunks of rock, smaller than a grain of sand, traveling faster than a bullet. Armor was out of the question – it would add too much weight. What were the chances of a meteorite hit, and how damaging would it be? No one knew. The Saturn I missions SA-8, -9, and -10 were used to launch the three Pegasus spacecraft in 1965.

The Pegasus missions were considered by NASA in 1962, and contracted to Fairchild Hiller Corporation. Design and development took place at their facilities in Bladensburg and Rockville, MD, with assembly in Hagerstown, MD. Pegasus was a secondary payload on the Saturn vehicle, with the primary payload being a boilerplate Apollo spacecraft. The Apollo boilerplate acted as a payload fairing for the Pegasus spacecraft, which was stored inside what would have been the Apollo Service Module. The Pegasus was a 3,200 pound satellite in low Earth orbit, designed to study micro-meteoroid impacts, an area that was relatively unknown at the time. The satellite had large 95-foot wing panels that folded out from the satellite body, and included 116 detectors, a data and power system, and a telemetry and tracking system. A lot was learned from the missions besides the micro-meteoroid environment. The Pegasus provided information on the thermal effects of surface coating in space, the susceptibility of electronics to the radiation environment, the orbital thermal environment, flight dynamics characteristics, and many other factors.

The Pegasus was a very large and heavy payload, but, with the Saturn, size and weight were not of much concern. Folded in launch configuration, the Pegasus was 17 feet, 4 inches high, 7 feet wide, and 11 inches deep. It was constructed of aluminum alloy. The large deployed wings contained penetration surfaces for the measurement

of micrometeorite impact. The wings had a total surface of 2,300 square feet.

The 11- by 16-inch wing panels were subdivided into 62 logic groups of from two to eight capacitors each. The capacitors are interconnected so that the satellite electronics package saw each logic group as one capacitor. A meteoroid hit on any panel was registered as a hit on the logic group in which that panel was located. Some capacitors on Pegasus I shorted in orbit, and it was necessary to remove logic groups; i.e., disconnect good or bad capacitors from the overall detection system. A new fusing arrangement was incorporated in the meteoroid detection system of Pegasus to fuse each capacitor individually. Before launch, the Pegasus satellites were known as A, B, and C.

A single malfunctioning capacitor left the other capacitors in the same logic group operating. When a malfunction occurred which was serious enough to warrant disconnection of the entire logic group, this could be done by ground command. The fusing arrangement worked successfully on Pegasus B and was installed on Pegasus C. The fuses could be blown by 50 milliamps. The ground command to blow a capacitor fuse could "heal" the capacitor instead of blowing the fuse, depending upon the cause of the short. Each capacitor "healed" in this manner was a bonus benefit. Each time a capacitor was penetrated by a meteoroid, the material removed by the impact was vaporized, forming a conducting gas which discharged the capacitor. The gas, or plasma, dissipated almost immediately and the capacitor recharged within three one-thousandths of a second. The recharge event was what was recorded.

If seen on the screen of an oscilloscope, the "blip" caused by a penetration and momentary discharge of the capacitor would be a sharp saw-tooth below the horizontal line. These blips were characteristic for each group of panels, providing a means of determining which group contained the penetrated panel.

When a panel was penetrated, several items of related information

were recorded, including a cumulative count of hits classified according to panel thickness; an indication of the panel group penetrated; the attitude of the satellite with respect to both the Earth and the Sun, the temperature at various points on the spacecraft, the time at which each hit was recorded, and the condition of the power supply and other equipment supporting overall spacecraft operation.

Various levels of impact energy were differentiated through the use of panels of three different thicknesses. Directional information was gained by using a combined solar sensor-Earth sensor system. The aluminum sheets of the wing assemblies were separated by a layer of polymer plastic, forming a capacitor. It was charged with 40 volts. There are capacitor panels on both sides of the wing assembly, a total of 416 separate detector panels. In addition, the spacecraft determined its attitude with respect to the Earth and Sun, using Earth and solar aspect sensors. A backup mode was spin-stabilization.

The Pegasus electronic system registered meteoroid penetrations of panel groups and stored a record of panel thickness, group number, and time of penetration. Pegasus attitude and certain temperatures were recorded on a timed schedule. The storage for the data was a 30,080 bit magnetic core memory unit. This could nominally hold the data for 6 to 8 hours of operation. The memory was read-out and transmitted 6 times, for redundancy, then cleared. This required about 1.5 minutes.

The Pegasus spacecraft was to detect meteoroids in the mass range of 10^{-7} to 10^{-4} grams, leading to an understanding of the on-orbit meteoroid environment in terms of density and direction. The measurements were taken between 500 and 800 kilometers. The detectors array used 116 capacitors of varying thicknesses over 185 square meters of area. Both real-time and stored data transmission were provided.

A new capacitor fusing arrangement was used on the second Pegasus after short circuits in the Pegasus I detection system hampered the capabilities of that satellite. This new system was

working well after one month. It provided the ability to disconnect a single malfunctioning capacitor detector while leaving other capacitors in the same group of panels working. Thirty-six capacitors on Pegasus were found to be working improperly during the first four weeks and were disconnected by ground command to prevent a drain on the satellite's power supply. Of these 36 capacitors, four were isolated and disconnected.

Pegasus-2 returned data until August 29, 1968. It reentered the atmosphere on November 3, 1979. Another potential use of the third Pegasus experiment was announced in NASA Press Release 65-232 in July 1965. This was to attempt to return to Earth samples of the meteoroid punctured metal, with hopefully captured micro-meteoroids. The Press Release states the purpose:

“This flight's primary purpose is to add information on the frequency of meteoroids to be encountered in near-Earth environment, for use in the design of future manned and unmanned spacecraft. The information was vitally needed with the increased emphasis on larger, long-life spacecraft, and the mission of the three-flight Pegasus program was to provide data necessary to determine the magnitude of the meteoroid hazard.”

“The engineering experiment consists of 4-8 aluminum sub-panels or "coupons" attached to Pegasus which could be quickly unhooked by an astronaut on an EVA and carried back to Earth in a Gemini or Apollo capsule. NASA officials emphasize that no decision has been made for an astronaut to rendezvous and retrieve the panels.” Keep in mind, this was before any manned Apollo Capsule had flown.

“Although numerous experiments have been conducted in space, no materials punctured by meteoroids have been returned so far. Meteoroids are the countless small particles of matter flying in space at great speeds. When they enter the Earth's atmosphere, they burn -- as meteors - and those that reach the ground are known as meteorites.”

At the time of the third Pegasus launch, the previous two Pegasus spacecraft were still on-orbit, returning data. Additional data on the micrometeorite environment was still coming in from Explorer XXIII, launched in 1964.

Skylab

After the Apollo program, with some spare Saturn's sitting around, the next project was the Skylab space station. This used a Saturn S-IVB upper stage as the structure for the station, launched by a Saturn-V with live first and second stages. The hydrogen fuel tank was re-purposed into the crewed facility. The payload to orbit was 170,000 pounds. The station was 82 feet long, 56 feet wide, and 36 feet in the other direction. It was quite visible from Earth, when the solar arrays caught the glint of the Sun. Astronauts were carried to the facility in-orbit on three missions in 1973-1974 by Apollo command and service modules launched on Saturn-1b vehicles. A second Saturn-1b and Apollo stack was kept in standby in case a rescue mission was needed. There are no documented cases of problems with orbital debris, but the 170,000 pound Skylab itself posed a disposal problem

There were plans to use the Shuttle to repair and reboost Skylab, but the timing did not work out. Skylab was in orbit until 1979, when it reentered the atmosphere, splashing into the Pacific Ocean near Perth, Australia. A few pieces of debris were found on land.

Liquid waste was not recycled in Skylab as it is on the current ISS. Liquid and solid waste went into the large Oxygen tank in the facility. It burned when Skylab re-entered.

The German Space Agency, DLR, developed the designs for the DEOS (Deutsche Orbitale Servicing Mission) robotic spacecraft. It was supposed to be capable of capturing an “un-cooperative” target, which would then put into a “destructive re-entry”. This is intended for tidying up orbital debris. Unfortunately, no funding has been forthcoming for this project.

NASA Orbital Debris Program Office

The NASA Orbital Debris Program Office is hosted at the Johnson Space Center, in Houston, Texas. Under their guidance, orbital debris models are developed and tested. Some models are used to predict future orbital debris environments. Orbital debris is tracked optically and via ground based radar. Examining spacecraft parts that have been returned from orbit by Shuttle-based servicing missions are very useful. The Shuttles themselves provided good examples of debris hits. Models are validated by JSC's Hypervelocity Impact Technology Facility.

The Inter-agency Space Debris Coordination Committee consists of members of 10 space-faring countries, and ESA, and addresses the growing problem.

The U. S.'s Orbital Debris Mitigation Standard Practices addresses the debris problem. It defines mitigation standard practices for satellites and upper stages to control release of particles greater than 5 mm, that will remain on-orbit for 25 years or more. A part of this is to assess the mission in terms of limiting the probability for explosion. This applies to all onboard sources of stored energy. Spacecraft are required to be designed such that collisions with debris smaller than 1 cm will not cause loss of control. Lethal, non-trackable debris is defined as that less than 10 cm. The U.S. Space Surveillance Network can track to 10 cm in LEO, or 1 meter in Geo.

End of life disposal is also addressed in three areas, atmospheric reentry, storage orbit, and retrieval. The reentry option assumes that the atmospheric drag will cause reentry within 25 years. This may involve the deployment of drag enhancement devices. Since even Cubesats are subject to this restriction, specific drag-enhancements for them have been developed. Reentry presents another problem, that of danger to humans and structures on the ground. The satellite must be re-entered in such a way that it enters the ocean in a remote location, with a 1 in 10,000 chance of human casualty. So far, so good.

A second option is maneuvering to a storage, or “graveyard” orbit. This doesn't solve the problem, it just postpones it. In the future, we can foresee an industry of spacecraft recycling in orbit. Between LEIO and medium orbits, the spacecraft is supposed to be placed with a perigee above 2,000 km, and an apogee below 19,700 km (below synchronous orbit). For medium altitude orbits, up to GEO, the storage orbit is a perigee above 20,700 km, and a apogee above 35,300 km. This will be below synchronous altitudes. For geosynchronous altitude, the graveyard orbit is 300 km above the geosynchronous altitude. If the spacecraft is in a heliocentric orbit (around the Sun), it can be maneuvered to collide with the Sun.

The third option is retrieval, which is difficult now with the retirement of the Space Shuttle. That also makes the option of on-orbit repair moot at the moment, but NASA is actively exploring in-orbit robotic repair. Active removal involves more than technical issues. There are legal and ownership issues. On the high seas, it is the law that if you retrieve an un-crewed ship, it is yours. That's not true in space.

The RemoveDebris Project is addressing some possible solutions at the Surrey Space Centre ie U.K. It is going to the ISS, and deployed by the crew. It comes with its own debris – several smallsats. These will be released, and RemoveDebris will attempt to net them. It's main approach is a harpoon. The third part of the technology demonstration is that it will be sent into the atmosphere to burn up, using a 10 square meter drag chute. As opposed to most missions, reentry and burning are the goals.

The Remove Debris mission was deployed fro the ISS in mod-September, 2018, and worked as expected. The net deployed properly. The Cubesat target expanded a balloon to increase its size. It is expected to reenter within a month. The next step is for the clean-up spacecraft to test out its harpoon with a flat target it will deploy, then deploy a sail, which will expedite reentry.

Airbus Industries is trying a variation of this approach for the elimination of Envisat Earth Observation Platform, a defunct ESA Mission launched in 2002. It is somewhat embarrassing to have the world's largest environmental satellite cluttering up orbit. It masses some 8 metric tones. A harpoon penetrator is fired with compressed gas, and easily penetrates the 3 cm composite honeycomb body panels. Then a set of spring loaded barbs extend, making the harpoon impossible to pull out. This harpoon is larger than the one considered for the RemoveDebris Project.

After the harpooned spacecraft is captured, the capturing satellite does a controlled reentry.

Tracking Junk, NORAD

Orbital Debris is tracked by radar. NORAD, the North American Aerospace Command, based in Colorado, tracks all detectable orbital entities, from large satellites to space junk, zombie-sats, and the larger pieces of debris, as well as near-Earth asteroids. The U. S. Space Surveillance Network can see objects 10 cm. or greater. They are deploying a new large telescope to improve their view of debris. This Space Surveillance Telescope will be able to see debris at Geosynchronous altitudes.

NORAD puts all this up on a website, in a standard format called the “two-line element” (TLE). This contains the Keplerian orbital elements, the set of data describing the orbit of anything around the Earth, for a given point in time (epoch). It is a legacy format from the 1960's, that still works. It includes two data items of 80 ASCII characters each (an IBM punch card format).

Here is the format and contents of Line 1 (courtesy, Wikipedia).

Field	Column	Content
1	01–01	Line number
2	03–07	Satellite number
3	08–08	Classification (U=Unclassified)

4	10–11	International Designator (Last two digits of launch year)
5	12–14	International Designator (Launch number of the year)
6	15–17	International Designator (piece of the launch)
7	19–20	Epoch Year (last two digits of year)
8	21–32	Epoch (day of the year and fractional portion of the day)
9	34–43	First Time Derivative of the Mean Motion divided by two
10	45–52	Second Time Derivative of Mean Motion divided by six (decimal point assumed)
11	54–61	BSTAR drag term (decimal point assumed)
12	63–63	The number 0 (originally this should have been "Ephemeris type")
13	65–68	Element set number. Incremented when a new TLE is generated for this object.[10]
14	69–69	Checksum (modulo 10)

Here is the format of line 2:

Field	Columns	Content
1	01–01	Line number
2	03–07	Satellite number
3	09–16	Inclination (degrees)
4	18–25	Right ascension of the ascending node (degrees)
5	27–33	Eccentricity (decimal point assumed)
6	35–42	Argument of perigee (degrees)
7	44–51	Mean Anomaly (degrees)
8	53–63	Mean Motion (revolutions per day)
9	64–68	Revolution number at epoch (revolutions)
10	69–69	Checksum (modulo 10)

You can also use this service:

<http://www.celestrak.com/NORAD/elements/>

Need to watch out for space debris? Go here:

<http://satellitedebris.net/Database>.

Wrap-up

We have made a mess in various Earth orbits. We have crashed spacecraft onto the moon, Venus, Mars, and Jupiter. At some point, we have to recycle, not dispose of. The ISS will be decommissioned, and quite a few parts can and will be used in follow-on facilities. Besides the concept of mining the asteroids, there is the feasibility of recycling old satellites.

The clean-up of the space debris problem is less technical than political, legal, and economic. There is no International agreement covering space debris, but the United Nations Committee on the Peaceful Uses of Space has issued guidelines. The U.S. is developing a “one-up, one-down” policy attached to its launch license procedure. This involves the capture and disposal of a derelict satellite, after the primary mission is deployed.

The evolution of on-orbit robotic repair vehicles will lessen the number of derelict spacecraft in orbit by refueling and repairing them when possible, but could also attach a de-orbit rocket. A large number of projects for orbital debris mitigation have been studied, but these are expensive. We probably won't see any action until there is a “major event.”

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Glossary

AIAA – American Institute of Aeronautics and Astronautics.

Apogee – altitude of an orbits closest approach to Earth.

AR&D – Autonomous Rendezvous and Docking.

ASAT – anti-satellite (weapon).

ASIN – Amazon Standard Inventory Number

ATP – authority to proceed.

BAA – Broad Agency Announcement (U. S. Government)

BMD – Ballistic Missile Defense

COPUOS – (U.N.) Committee on the Peaceful Uses of Outer Space.

CPU – central processing unit

CRADA – Cooperative Research and Development Agreement (U. S. Government and industry)

CSA – Canadian Space Agency.

DARPA – (U. S.) Defense Advanced Research Projects Agency.

DLR – German Space Agency (Deutsches Zentrum für Luft- und Raumfahrt)

DOF – degrees of freedom

ELV – Expendable Launch Vehicle.

ESA – European Space Agency

EVA – Extra Vehicular Activity- involving an Astronaut with suit and maneuvering unit in space.

FAR – (US) Federal Acquisition Regulations

GEO – geosynchronous Earth orbit, 22,236 miles.

GHz – giga (10^9) hertz.

Giga - 10^9

GOES – NASA/NOAA Geostationary Operational Environmental Satellite

Graveyard orbit – a place to park end-of-life satellites.

Gray - unit of radiation, =100 rad

GSFC – Goddard Space Flight Center, Greenbelt, Maryland. NASA Center for unmanned spacecraft near Earth.

HIT-F (NASA-JSC) Hypervelocity Impact Technology Facility

IADC – Interagency Space Debris Coordination Committee

IDD – Interface Definition Document.

Intelsat - International Telecommunications Satellite Organization.

IP – Intellectual Property

ISBN – International Standard Book Number.

ISS – International Space Station.

JAXA - Japan Aerospace Exploration Agency

JSC – NASA Johnson Space Center, Texas.

JSOC – U. S. Joint Space Operations Center

Kessler Syndrome – a cascade effect, where debris multiplies by collisions.

LDEF – Long Duration Exposure Facility

LEO – Low Earth Orbit

LIDS – Low impact docking system.

LSP – NASA launch services program.

LTG – LEO to GEO.

LV – launch vehicle.

MDA – (U. S.) Missile Defense Agency

MEO – medium earth orbit, above 2,000 km, below geostationary.

MES – mission extension services,

MEV-1 (Orbital-ATK) Mission Extension Vehicle-1.

mil – one thousandth of an inch; 0.0254 millimeter.

MMOD - micrometeoroid and orbital debris

MSFC – Marshall Space flight Center, Huntsville, Alabama.

NASA – National Aeronautics and Space Administration (USA)

NIST – National Institutes of Standards and Technology.

NOAA – National Oceanographic and Atmospheric Administration.
(USA)

NORAD – North American Air Defense command (USAF)

NAE – (U.S.) National Academy of Engineering.
NAS – (U. S.) National Academy of Science.
NRC – (U.S.) National Research Council.
NRL – U.S. Naval Research Center.
ODPO – (NASA) Orbital Debris Program Office
ODQN – Orbital Debris Quarterly News, from NASA, JSC.
OLEV - Orbital Life Extension Vehicles
OSSL - Orbital Satellite Services, LTD.

ORU – Orbital Replacement Unit.
ProxOps – proximity operations.
Perigee – point in an orbit furthest from the Earth.

POES – Polar orbiting environmental satellite.

RCS – reaction control system

RFI – Request for Information; radio frequency interference.

RNS – Relative Navigation System

RSGS – Robotic servicing of geosynchronous satellites.

SCM – Soft Capture Mechanism.

SIS – Space Infrastructure Servicing

Socrates – Satellite Orbit Conjunction Reports Assessing
Threatening Encounters in Space.

SPIE--the International Society for Optical Engineering.

SSCO – Satellite Servicing Capabilities Office, NASA, GSFC.

SSTL – Surrey Satellite Technology Ltd. (U.K.)

STS – Space Transportation System (USA) Shuttle.

TDRS – Tracking and Data Relay Satellite.

TLE – two line elements

ULA – United Launch Alliance, commercial launch services company.

Ullage – unusable fuel left in an “empty” tank.

USAF – United States Air Force.

Zombie-Sat – dead satellite posing a danger to other spacecraft

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